X-Ray Multi-Energy Introscopy Systems with New Semiconductor Scintillators

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Abstract

Theoretical background and data on the ways of practical realization are presented, related to the problem of detection of dangerous organic objects (explosives, drugs, etc.) in the presence of other organic substances with atomic number differing by no more than 20-30%. For this purpose, multi-energy X-ray introscopy is used. It has been shown that the "weakest link" in the existing multi-energy introscopes used for safety inspection and medicine are detectors of ionizing radiation. In particular, critical is the type of scintillator used in the low-energy detection subsystem. Data are presented on design principles and properties of combined detectors based on a new type of semiconductor scintillators (SCS) – $ZnSe(Te,O)$, with conversion efficiency of 19-22%, afterglow level less then $0.05\,\%$ after $10\,ms$, and radiation stability up to $500\,Mrad$. Results are given on the practical use of experimental samples of the low-energy detector subsystem based on the new SCS material in two-energy introscopes of the 4th and 5th generation.

Alarming tendencies towards increased danger of terrorism, expanding traffic volumes of illegal loads and enclosures of organic origin (explosives, drugs, components of chemical and biological weapons, etc.) indicate an increasing need for improvement of stationary and mobile radiation inspection means and instrumentation. One of the most promising directions in this field is development and application of multi-energy polydimensional (2D and 3D) X-ray introscopy systems (which are also of great interest for medical express diagnostics).

The existing safety inspection devices (SID) have rather high ability to detect metal objects and can also reveal organic materials on the background of inorganic environment. However, they do not ensure identification of explosives and drugs on the background of other organic materials, which is an essential drawback of the existing systems. Contemporary SIDs also generally fail in such specific applications as detection of organic inclusions (powders) in postal envelopes.

Possibility of property identification of the imaged objects with close values of the effective atomic number Z_{eff} by methods of multi-energy X-ray introscopy has been

considered for a single-channel and N-channel ($N \geq 2$) signal detection methods. In a standard approach, the structure of an object is synthesized using "phantoms" that correspond to the reference materials with known properties (e.g., calcium phosphate $Z_{eff}[Ca_3(PO_4)_2] = 17.38$ and water $Z_{eff}[H_2O] = 7.95$, or carbon $Z_{eff}[C] = 6$ and iron $Z_{eff}[Fe] = 26$ – in two-energy introscopy). Geometrical dimensions, including absorbing thicknesses Δ_j of the object elements, are determined by the 2D or 3D configuration of the detecting system. Reconstruction of the object structure is made by analysis of the signal amplitude $V_i = \eta(E_i)V_{0i}\exp(-\sum_j \mu_{ij}\Delta_j)$, where η is "conversion efficiency" of the detecting channel, V_{0i} – power rate of the quasi-monochromatic X-ray source with radiation energy E_i, μ_{ij} – integral (mainly, over photo- and Compton effects) absorption constant by different layers Δ_j of the object. Theoretical analysis and experimental data show that "synthesis" of the structure using single-channel detection can be done only approximately, qualitatively, not allowing identification of the structure elements Δ_j with close Z_{eff} values.

More precise analysis of the object structure requires introduction of additional separate channels for signal detection. Then even in the simple case of two-energy SID (with 2D- or 3D-configuration of the detecting system) it is possible to determine Z_{eff} [1] with high precision for different elements μ_j, and $Z_{eff} = F(V_{ij}; C_{ij}, Z_j^*)$, where C_{ij} and Z_j^* – are calibration parameters.

Thus, the key element determining functional parameters of the SID is a detector array composed of hundreds and thousands of radiation detectors, which are based on scintillator crystals. The scintillator characteristics are the main factor that determines and limits the general sensitivity and detectability of dangerous inclusions by the detectors and the SID as a whole. Basic limitations of scintillation parameters (afterglow, light output) and other properties (radiation hardness and stability, hygroscopicity, etc.) achieved with the best existing scintillators – $CsI(Tl)$, CWO, GSO, etc. – are the major factors that put limits to the capabilities of the existing SID.

Therefore, efforts in engineering and technology should be directed (in parallel with establishing theoretical base for SID of new generations) towards development of new types of scintillator crystals.

New prospects in this direction have been commenced by recent development of a new class of semiconductor scintillators (SCS) based on A^2B^6 compounds at the Concern "Institute for Single Crystals" (CISC), Kharkov, Ukraine. According to data X-ray-sensitive elements on the basis of $ZnSe(Te,O)$ have conversion efficiency of 0.19-0.22 exceeding that of $CsI(Tl)$ (0.15), technical light output of up to 120-150% with respect to $CsI(Tl)$, their afterglow level after $10-20\,ms$ is by 1-2 orders of magnitude lower ($\leq 0.03\%$) and radiation stability is more than 1000 times higher than those of $CsI(Tl)$ [2]. Preliminary data show that conductivity of scintillators of this type can be intentionally varied within 10 to 14 orders of magnitude. This might be important for development of scintillation detectors with surface-integrated photosensitive heterostructures based on A^2B^6 compounds [3].

To construct a two-energy X-ray introscopic SID, we chose $ZnSe(Te,O)$ crystals as scintillation elements for the low-energy detector subsystem of "scintillator $ZnSe(Te,O)$–Si-photodiode" type. Among all known scintillators used in X-ray introscopy ($CsI(Tl)$, CWO, GSO, etc.) SCS $ZnSe(Te,O)$ have the best complex of parameters, which ensure for detectors based on these crystals the highest abso-

lute radiation sensitivity (especially in the low energy range of $E_i < 50 - 70 keV$), steepness of $dV/d\rho$ signal transformation, as well as the broadest dynamic range due to high conversion efficiency of this SCS and low afterglow level.

It is also interesting to note that relatively low value of $Z_{eff}[ZnSe(Te,O)] \approx 32$, which is generally considered as disadvantage for a scintillator, is an important positive factor from the viewpoint of multienergy X-ray spectroscopy. This property allows SCS $ZnSe(Te,O)$ to be used in “sequentially located” two-energy detectors simultaneously in two different roles – as a scintillation element and as a low-energy radiation filter with low values of accumulation factor and scattering constants. In the high-energy detector subsystem, depending upon SID purpose, conventional scintillators – $CsI(Tl)$, CWO, etc. can be used.

Data are presented on the practical use of experimental samples of the low-energy detector subsystem based on the new SCS material in two-energy introscopes of the 4^{th} and 5^{th} generation by leading companies in Germany and Ukraine. Their detecting ability towards potentially dangerous organic inclusions has been shown to be substantially superior, with penetrating ability (steel) 150-200% higher, as compared with similar introscopes produced by leading USA companies, which used other kinds of scintillators.

[1] S.V. Naydenov, V.D. Ryzhikov, “Determining Chemical Compositions by Method of Multi-energy Radiography” *Technical Physics Letters*, vol. 28, 2002, pp. 357-360.

[2] V.D. Ryzhikov, N.G. Starzhinskiy, L.P. Gal’chinetskii, M. Guttormsen, A.A. Kist, and V. Klamra, “Behavior of New ZnSe(Te,O) Semiconductor Scintillators Under Doses of Ionizing Radiation”, *IEEE Trans. Nucl. Sci.,* vol. 48, # 4, 2001, pp.1561-1564.

[3] A.I. Focsha, P.A. Gashin, V.D. Ryzhikov, and N.G. Starzhinskiy, “Preparation and Properties of an Integrated System “Photosensitive Heterostructure-Semiconductor Scintillator” on the Basis of Compounds $A^{II}B^{VI}$, *Intern. J. Inorg. Mater.,* # 3, 2001, pp. 1223-1226.